Simulations of plasma responses due to RMP with BOUT++ code

BOUT++
Boundary Plasma Turbulence Code

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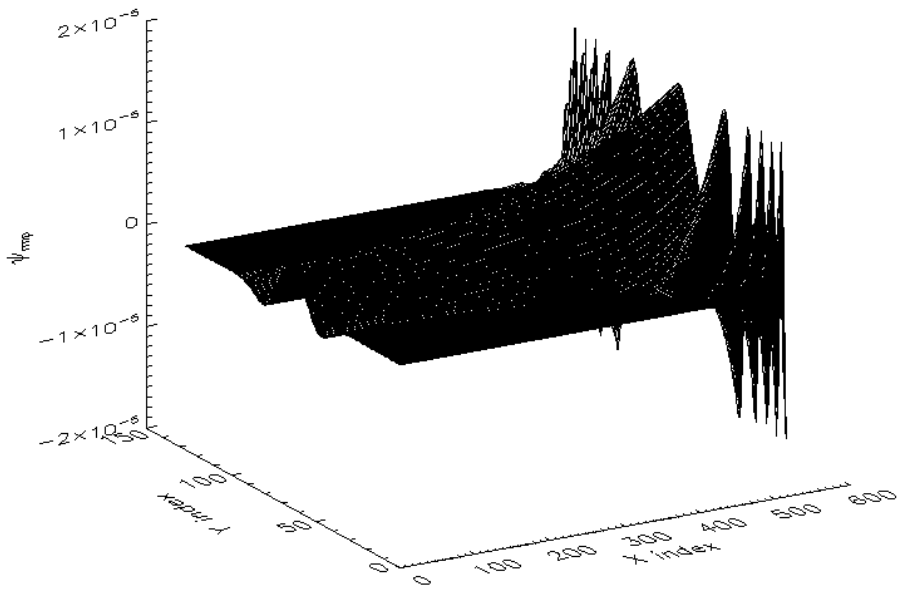
DPP12 Meeting of
The American Physical Society
October 29 - November 2, 2012. Providence, Rhode Island

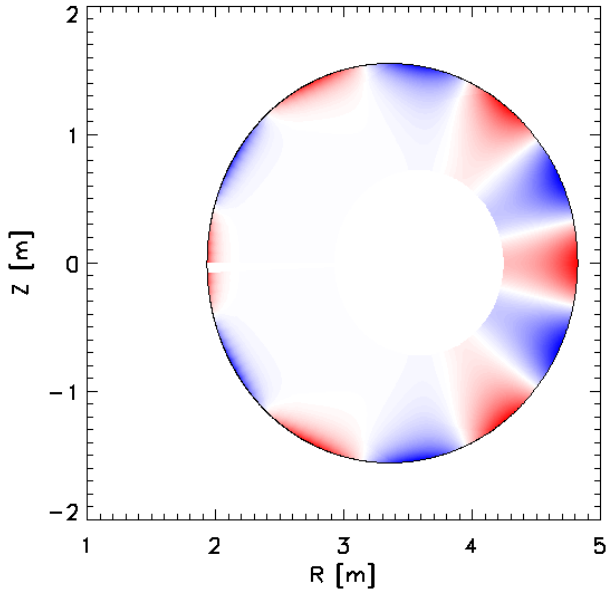
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and is supported by the China Natural Science Foundation under Contract No.10721505, the National Magnetic Confinement Fusion Science Program of China under Contracts No. 2011GB107001**. LLNL-PRES-597412.**

RMP field generation

- RMP field is set at the outer boundary surface and derived in the simulation area according to the equation:

$$\nabla_{\perp}^{2}\psi_{rmp}=0 \qquad \psi_{rmp}\,|_{r=a}=\psi_{0}\cos(m\theta+n\zeta)$$

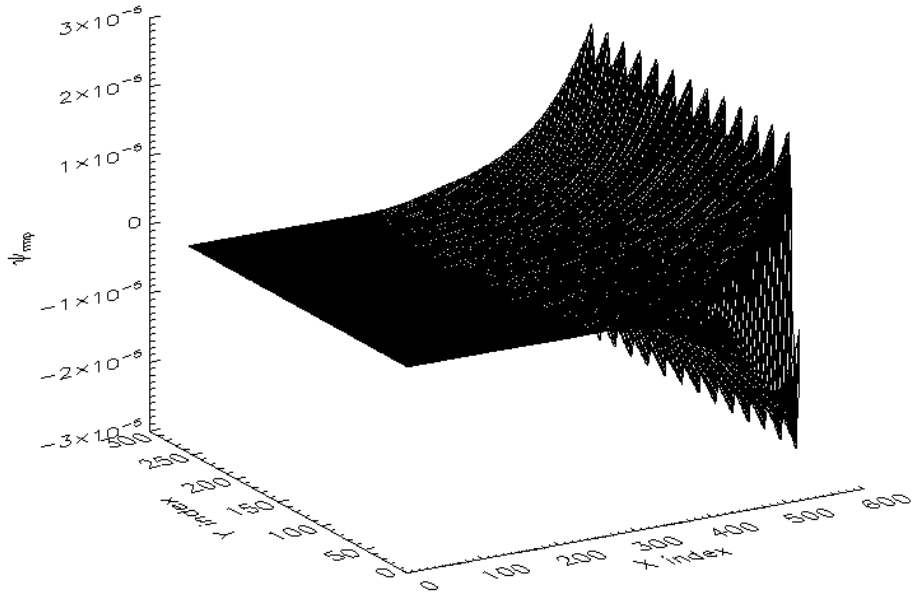


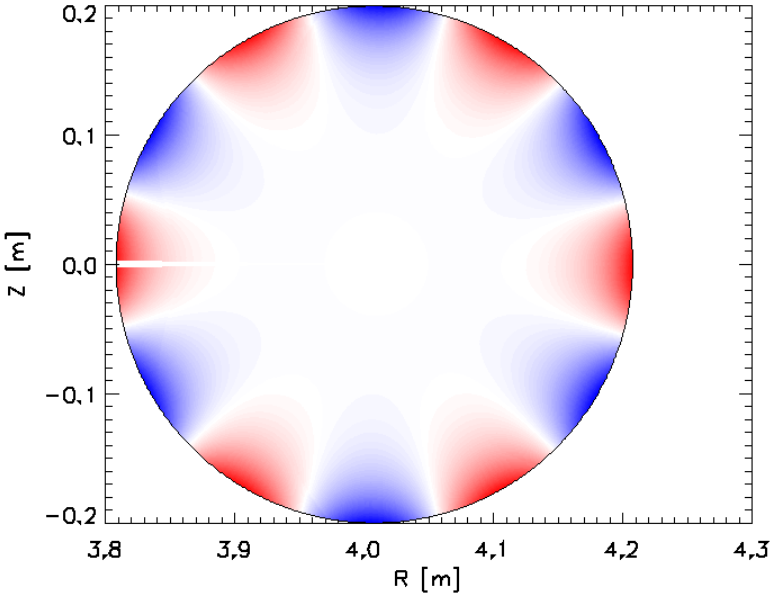


- The poloidal mode number is 6 and the toroidal mode number is 3.

In the case with higher R/a ratio grid file, the RMP is uniform in poloidal direction:

- High R/a ratio. m=6, n=3





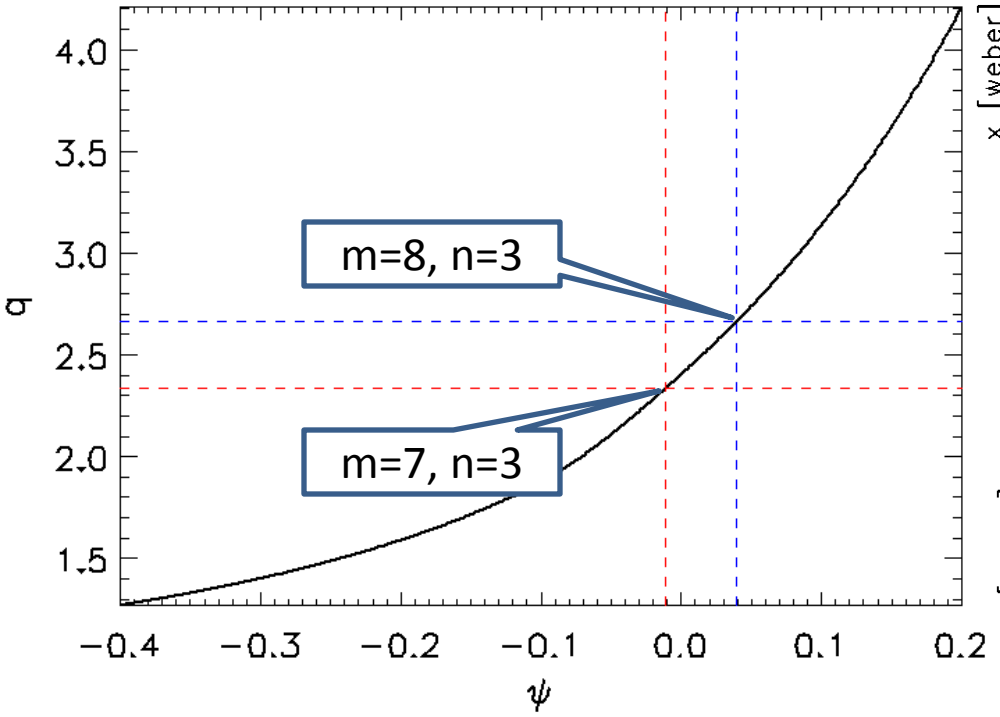
- In our simulation, the RMP is combined with the original magnetic field perturbation from P-B modes, to study the Plasma response due to RMP field.

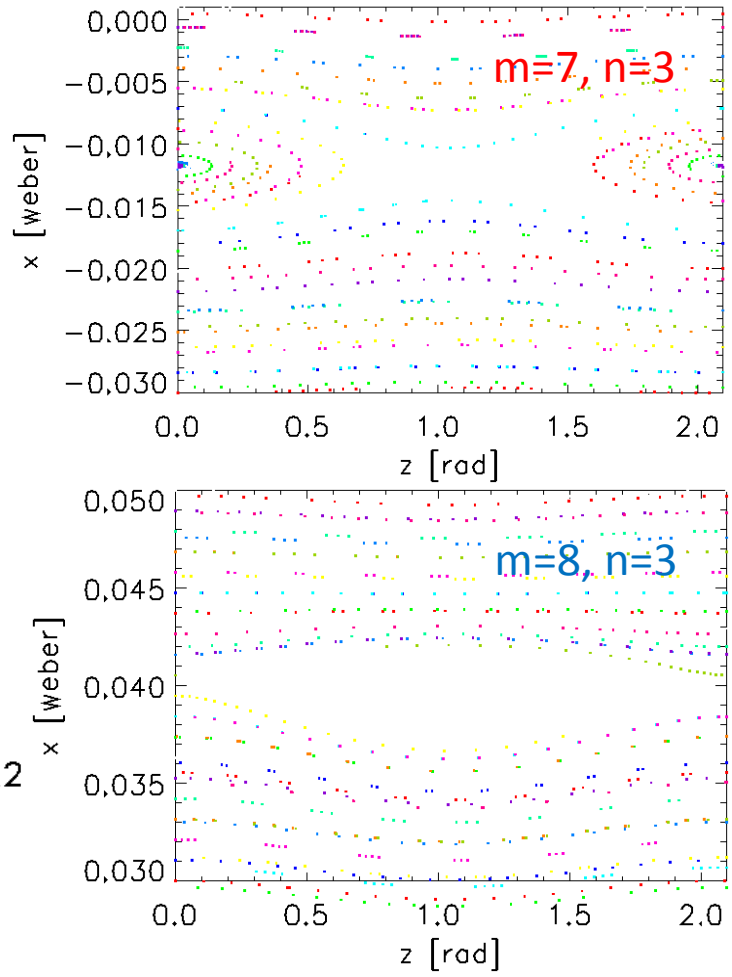
RMP induced the magnetic field island at the right radial position.

- RMP generate magnetic field island at the radial position where the resonant conditions are satisfied:

$$q = m/n$$

'q' is the safety factor. 'm' and 'n' is the poloidal and toroidal mode number, respectively.





Three-Field two-fluid equations with RMP

- **Equations modification:**

$$\rho\frac{\partial\omega}{\partial t}+v_E\cdot\nabla\omega=B_0^2(\vec{b}\cdot\nabla)(\frac{J_\parallel}{B_0})+2\vec{b}_0\times\vec{k}\cdot\nabla P$$

$$\frac{\partial\psi}{\partial t}=-\frac{1}{B_0}(\vec{b}\cdot\nabla)\phi+\frac{\eta}{\mu_0}\nabla_\perp^2(\psi+\psi_{rmp})-\frac{\eta_H}{\mu_0}\nabla_\perp^4(\psi+\psi_{rmp})$$

$$\frac{\partial P}{\partial t}=-\frac{1}{B_0}\vec{b}_0\times\nabla\phi\cdot\nabla P$$

$$\vec{J}_\parallel=\vec{J}_{\parallel 0}-\frac{1}{\mu_0}B_0\nabla_\perp^2(\psi+\psi_{rmp})$$

$$\omega=\frac{n_0M_i}{B_0}(\nabla_\perp^2\phi+\frac{1}{n_0Z_ie}\nabla_\perp^2 p_i)$$

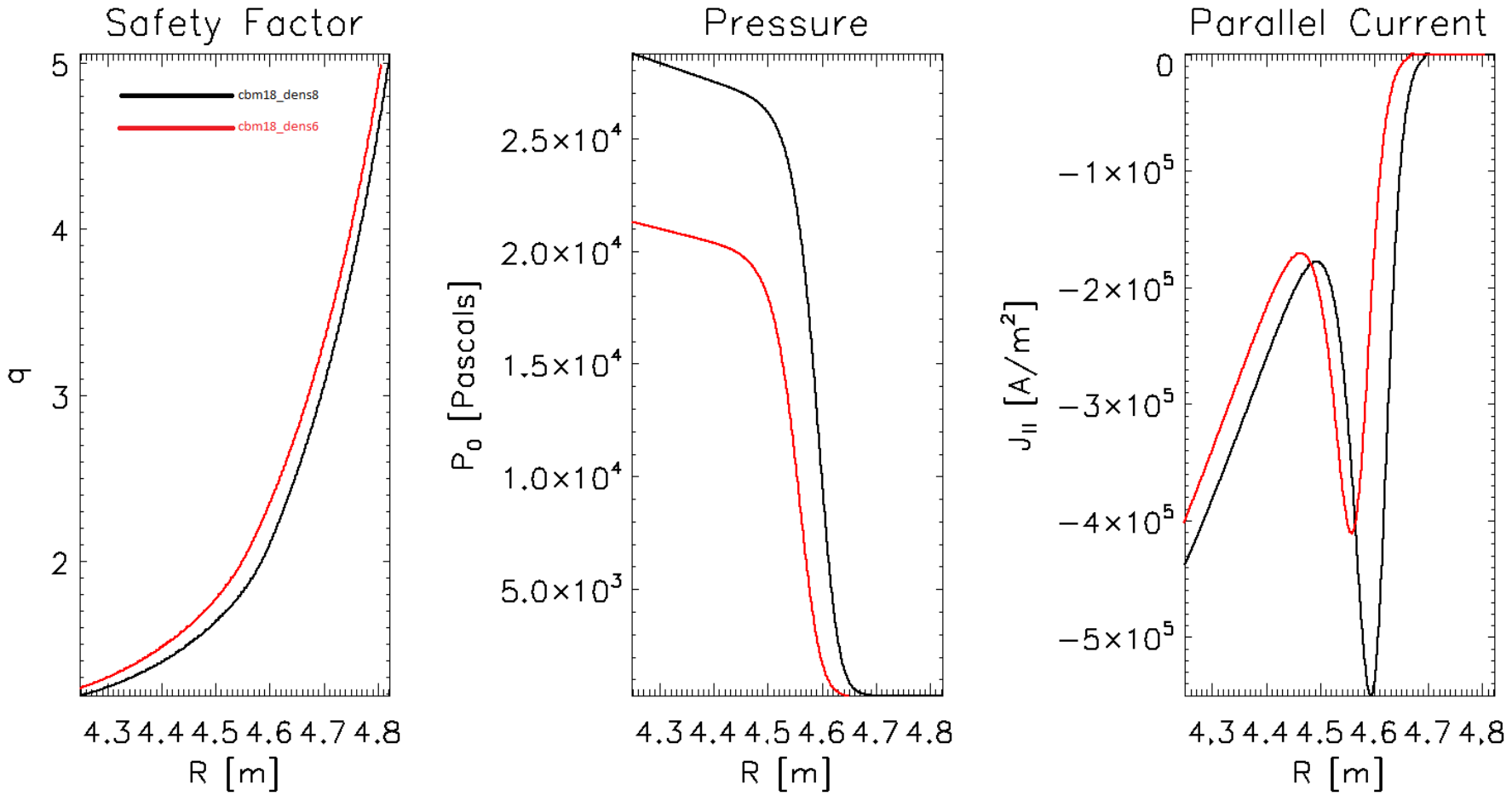
$$\vec{B}_1=-\vec{B}_0\times\nabla(\psi+\psi_{rmp})$$

$$\vec{b}\approx\vec{b}_0+\frac{\vec{B}_1}{B_0}=\vec{b}_0-\vec{b}_0\times\nabla(\psi+\psi_{rmp})$$

$$\nabla_\parallel=\vec{b}\cdot\nabla=\vec{b}_0\cdot\nabla-\vec{b}_0\times\nabla(\psi+\psi_{rmp})\cdot\nabla$$

Plasma Equilibriums and magnetic geometry

- In the simulations, two grid files (cbm18_dens8; cbm18_dens6) were used. Both of them are circular cross-section toroidal equilibrium generated by the TOQ equilibrium code. The difference between them is that 'cbm18_dens6' has a lower pedestal than the 'cbm18_dens8' equilibrium, thus has smaller P-B perturbations.

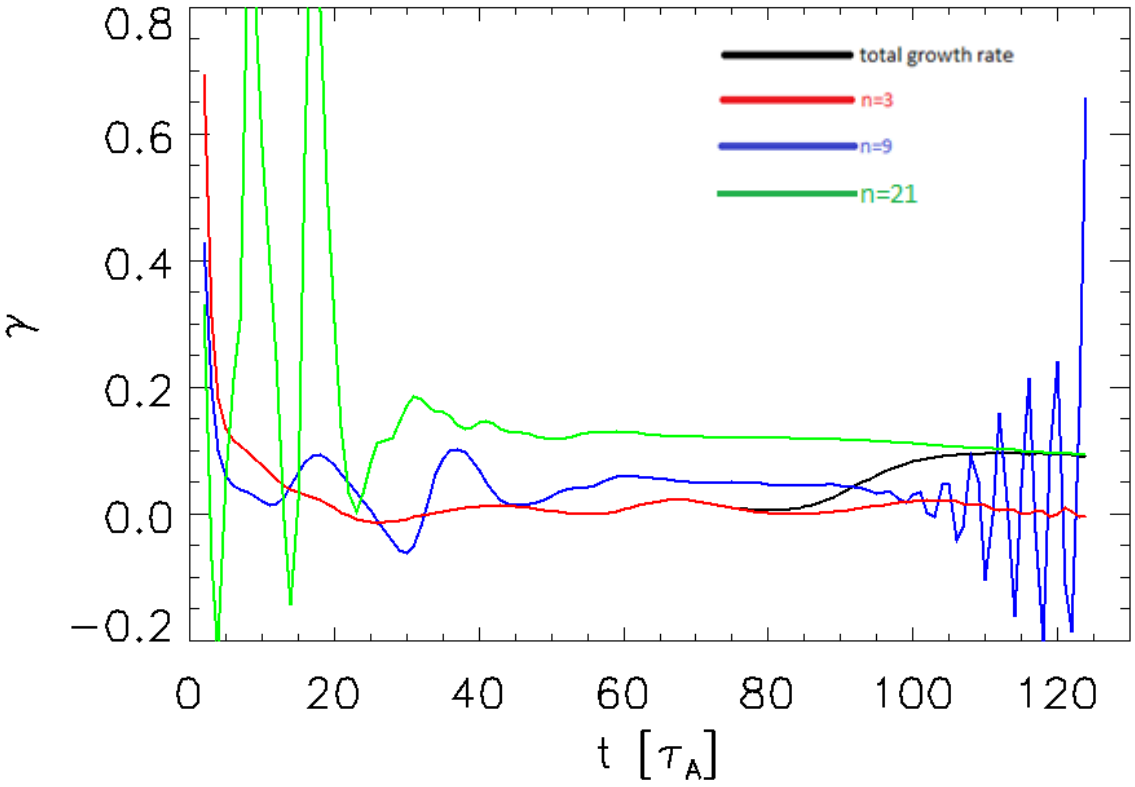


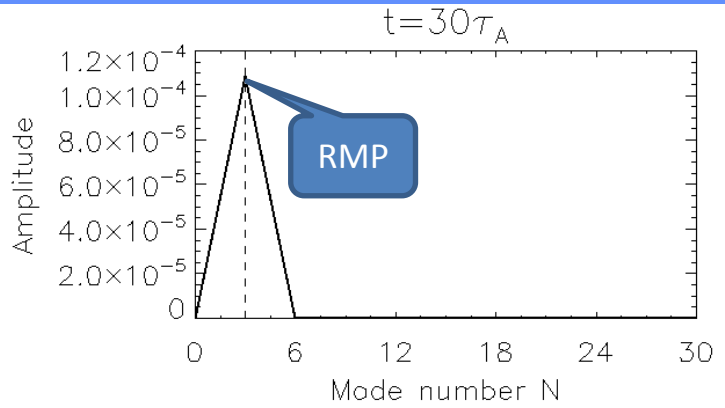
List of all the simulation cases

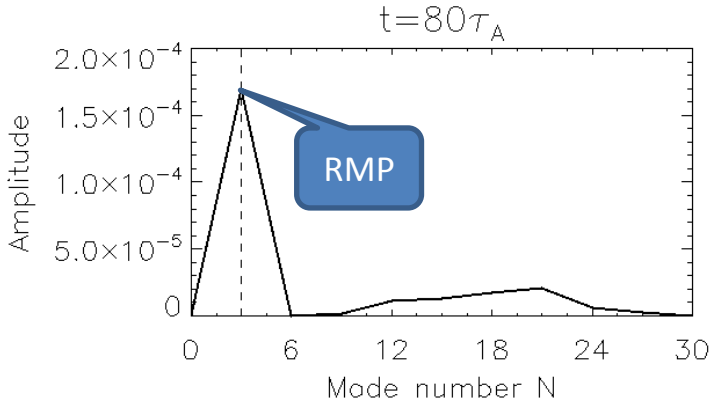
Case number	Plasma Equilibriums	RMP field	Initial perturbation mode number	RMP island position
Linear simulation				
Case 1	cbm18_dens6	m=6, n=3	n=9	Island aligned with the peak gradient area.
Case 2	cbm18_dens6	m=6, n=3	n=3	
Nonlinear simulation				
Case 3	cbm18_dens8	m=6, n=3	n=15	Island aligned with the peak gradient area.
Case 4	cbm18_dens8	m=7, n=3	n=15	Island aligned with the P-B mode magnetic field perturbation island but farther from peal gradient area.
Case 5	cbm18_dens6	m=6, n=3	n=15	Island aligned with the peak gradient area.
Case 6	cbm18_dens6	m=7, n=3	n=15	Island aligned with the P-B mode magnetic field perturbation island but farther from peal gradient area.

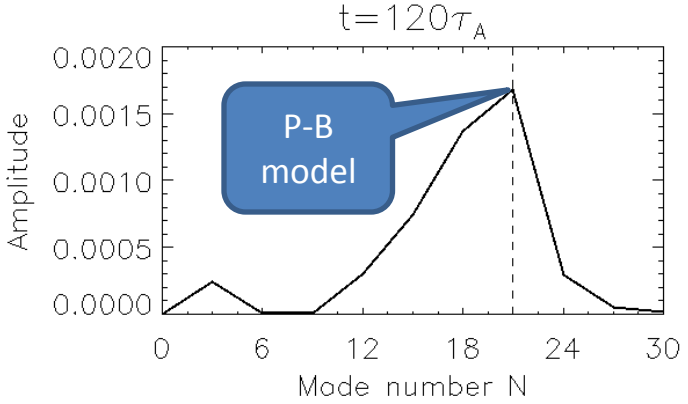
Linear simulation results, case 1

- Case 1:
- RMP: m=6, n=3
- The initial perturbation: n=9.
- Equilibrium: cbm18_dens6
- At beginning, the RMP is dominated. Then the perturbation with higher mode number grows up, and become dominated.



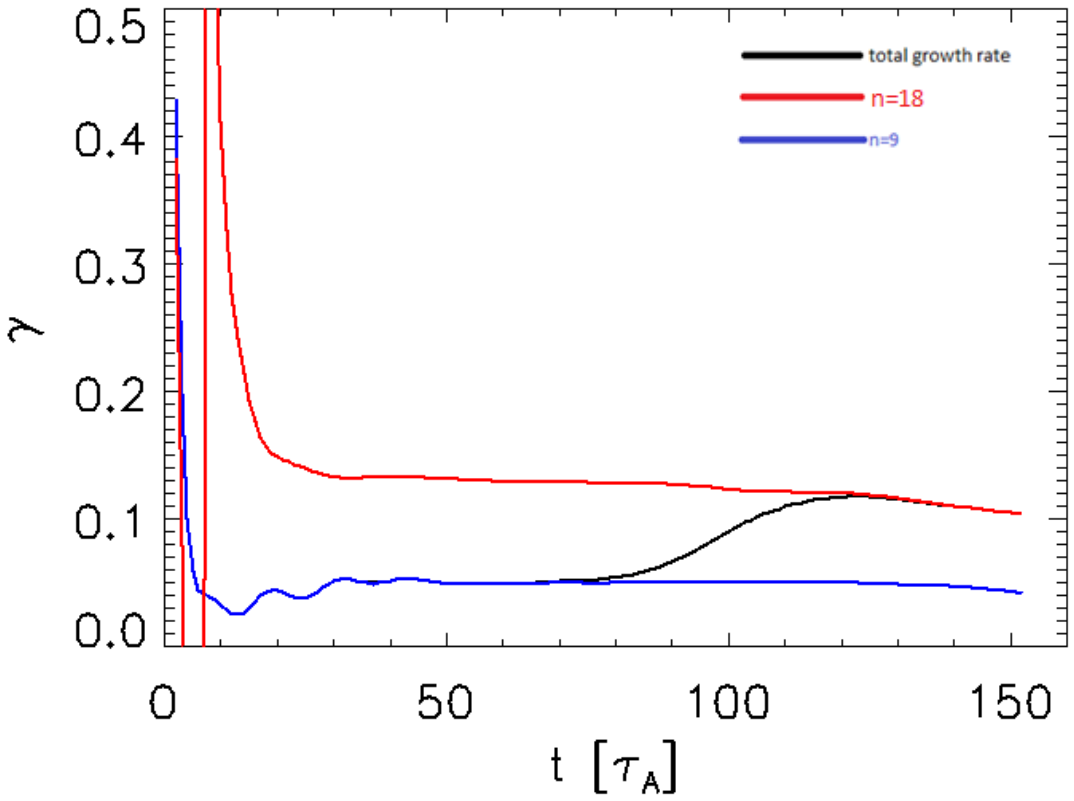


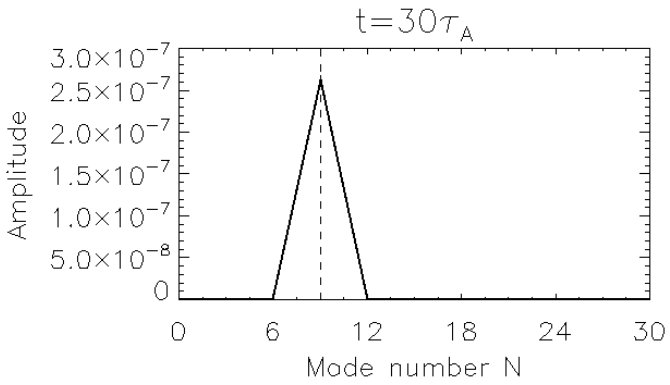


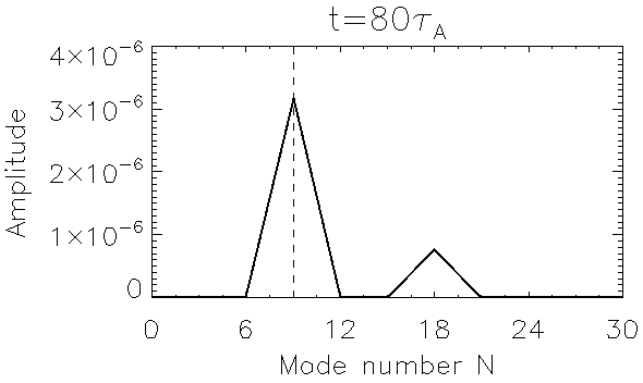


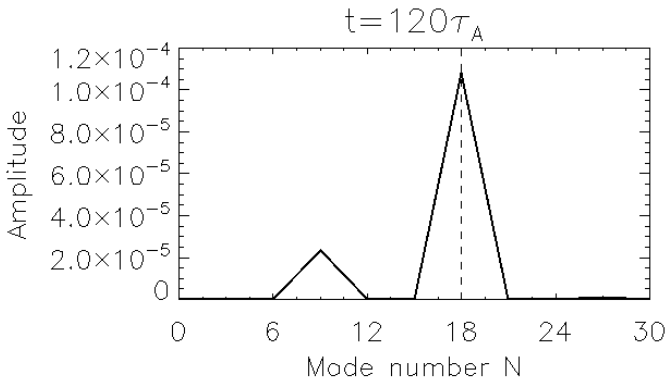
Linear simulation results, case 1

- The growth rate of the perturbation with different mode number of the case without RMP:



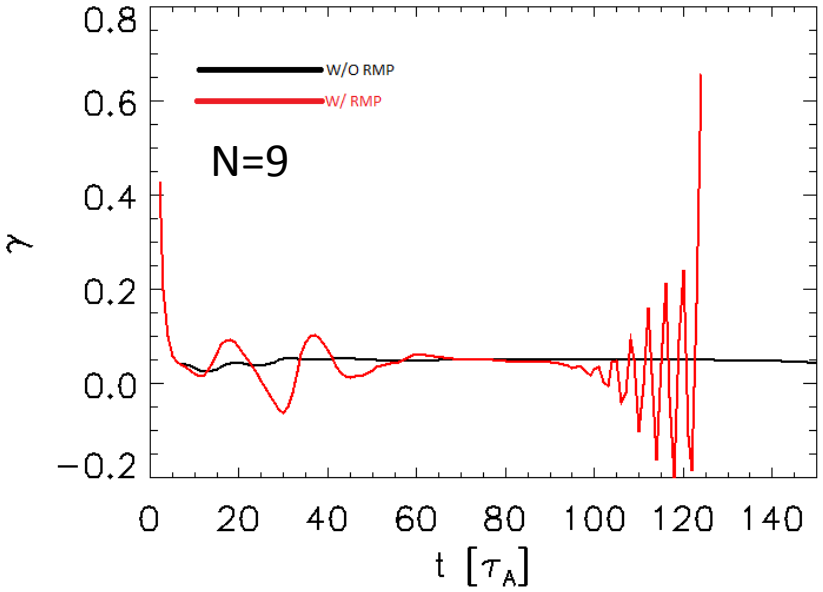






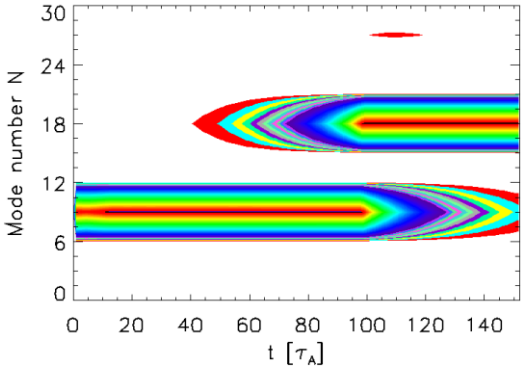
The RMP effect on the case 1

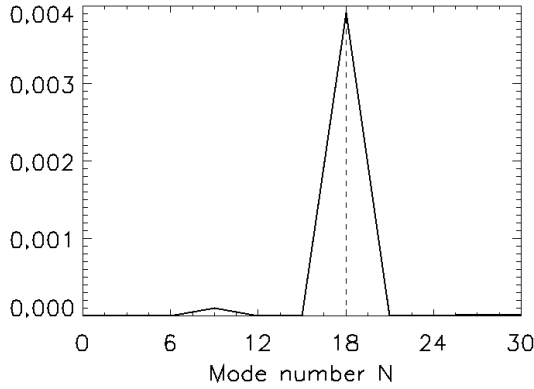
The growth rate of the perturbation with n=9 of the cases with or without RMP.



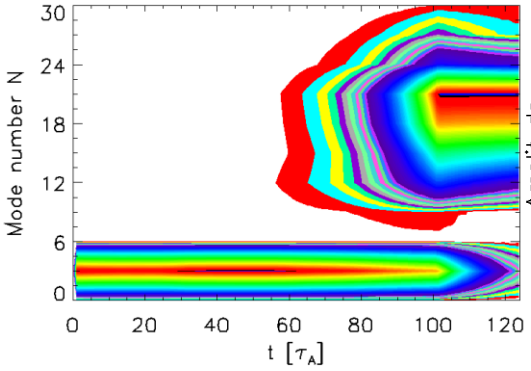
- RMP stabilizes n=9 mode.

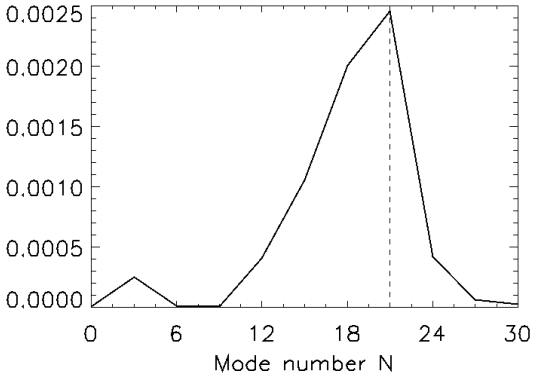
Case without RMP





Case with RMP





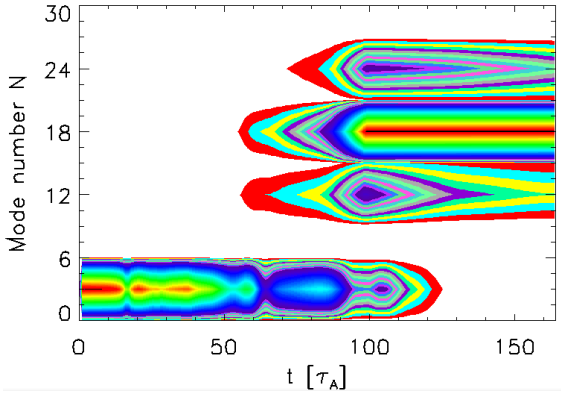
Time tracing of spectrum

The spectrum at last step

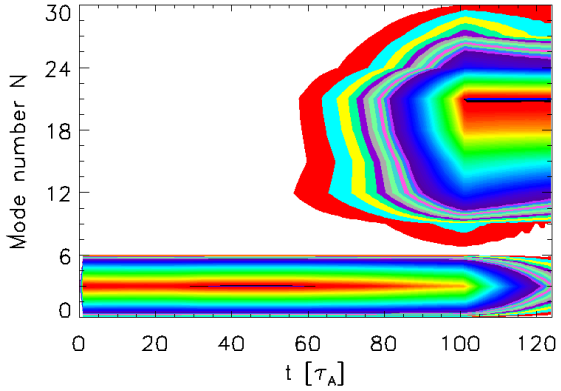
The RMP effect on the case 2

- Case 2:
- RMP: m=6, n=3
- The initial perturbation: n=3.
- Equilibrium: cbm18_dens6

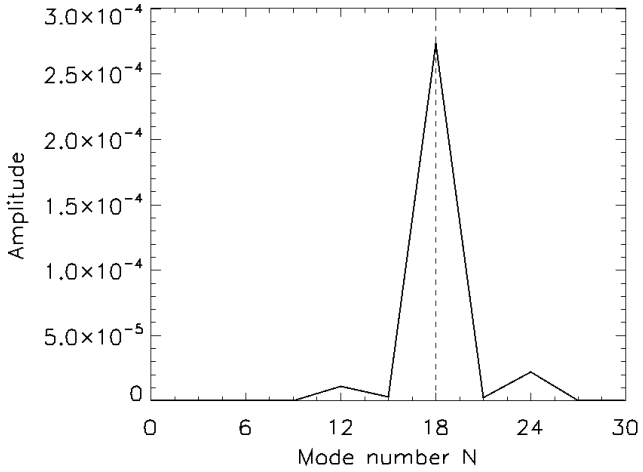
Case without RMP

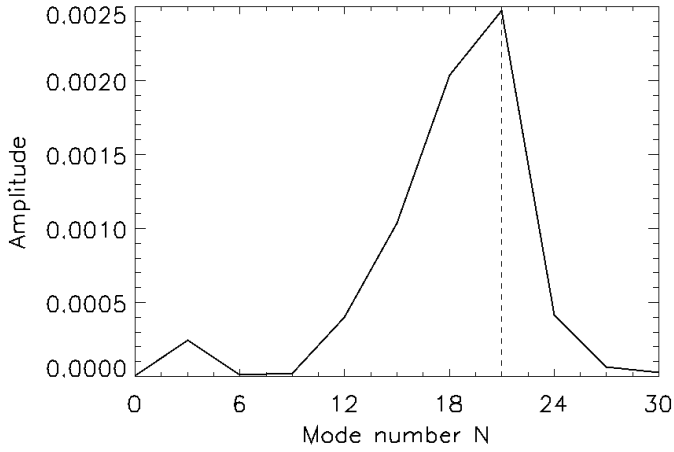


Case with RMP



Time tracing of spectrum

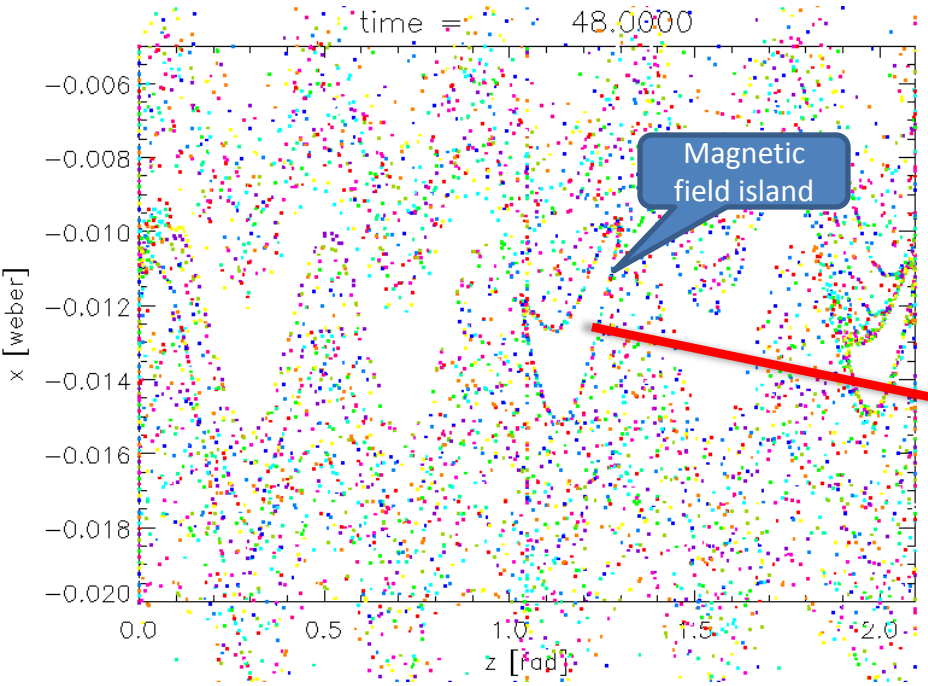


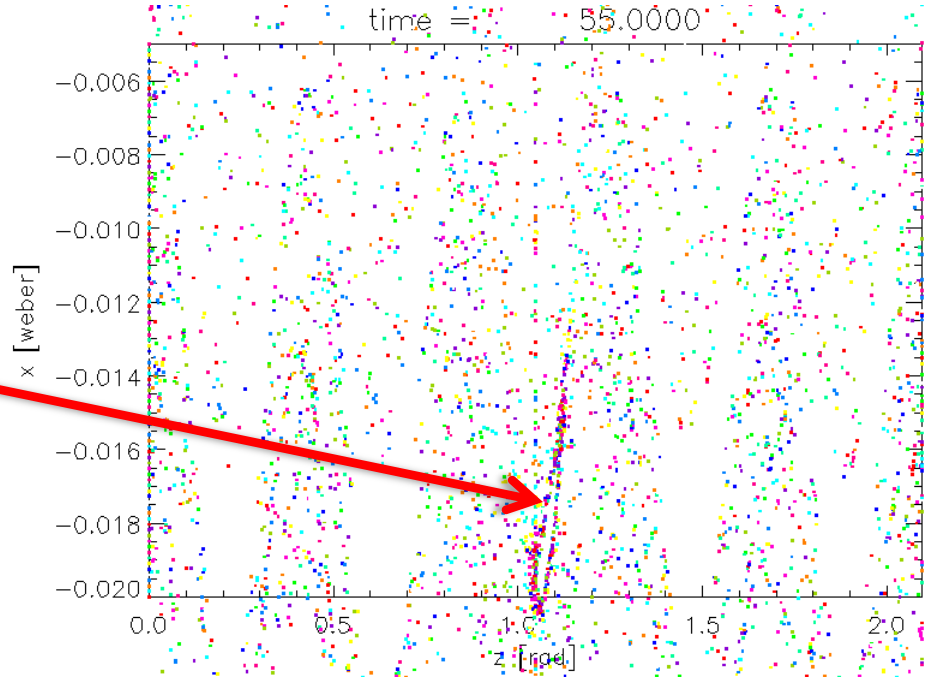


The spectrum at last step

Nonlinear simulation results

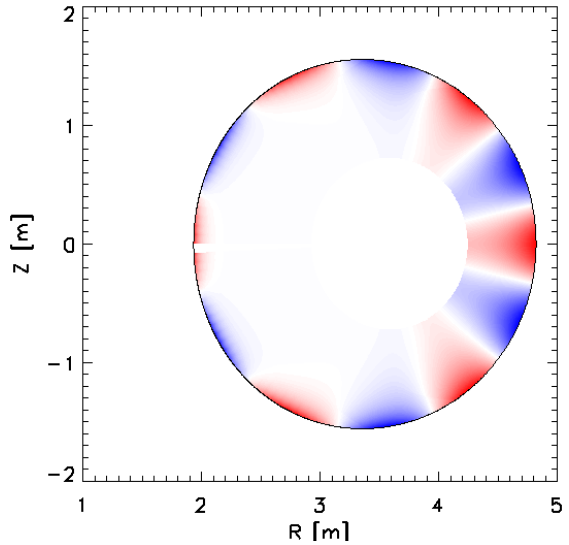
- In nonlinear simulation, the magnetic field reconnection occurred. At the beginning of the ELM crash, the magnetic field perturbation generates magnetic field islands at pedestal; Later, the magnetic field island elongate in radial direction.

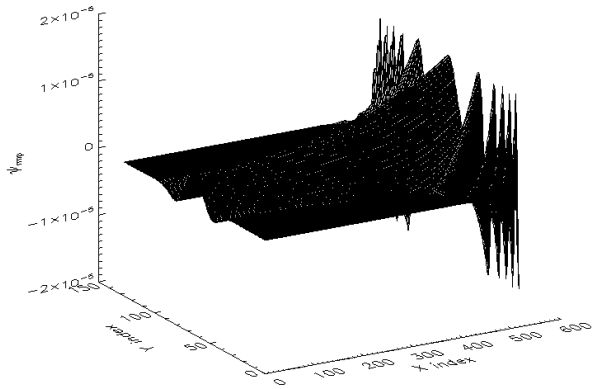


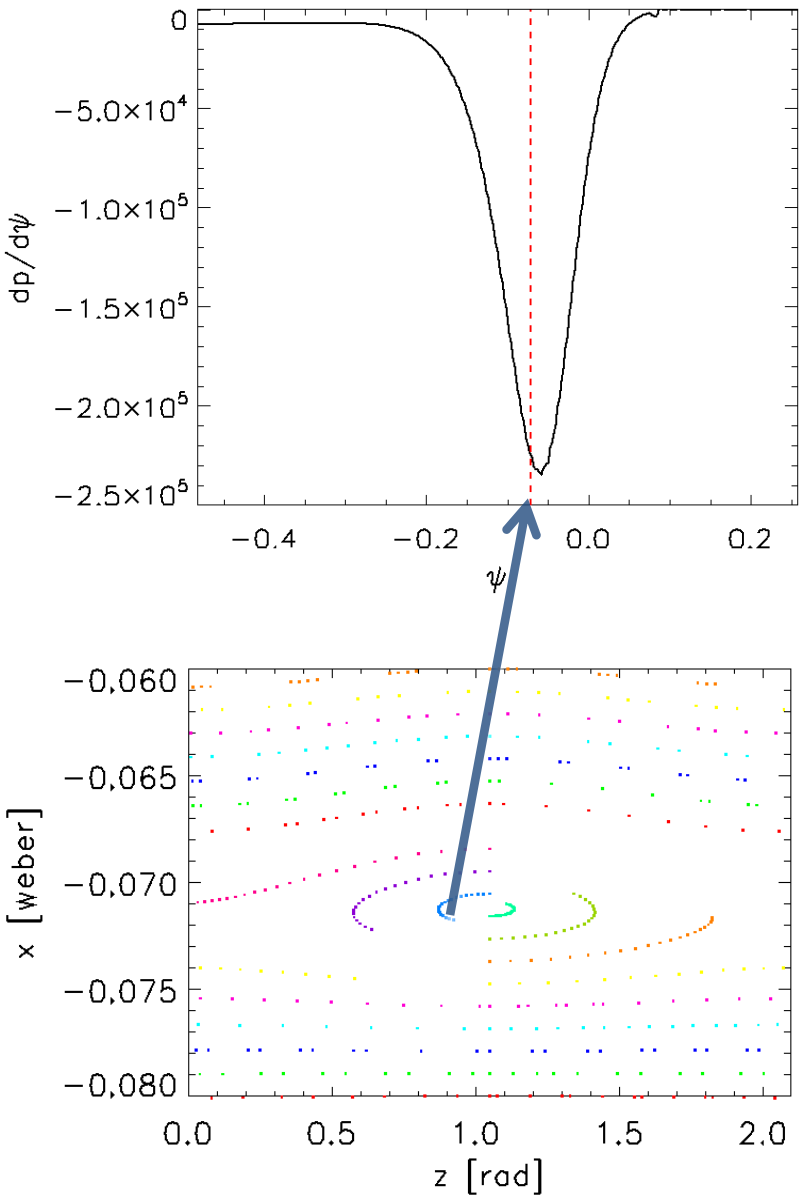


Nonlinear simulation, case 3

- Case 3:
- RMP: m=6, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens8



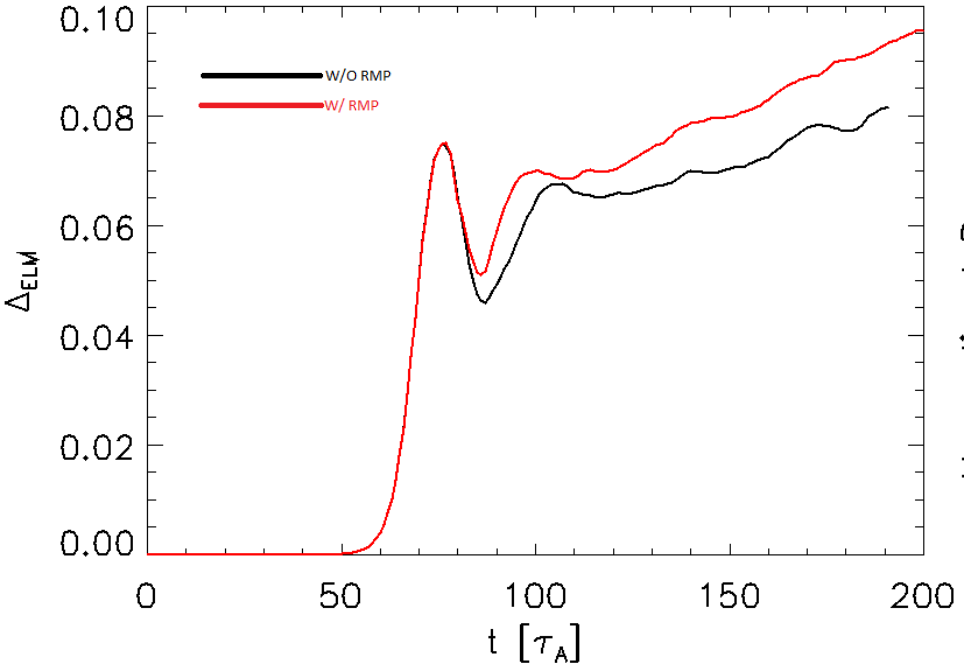


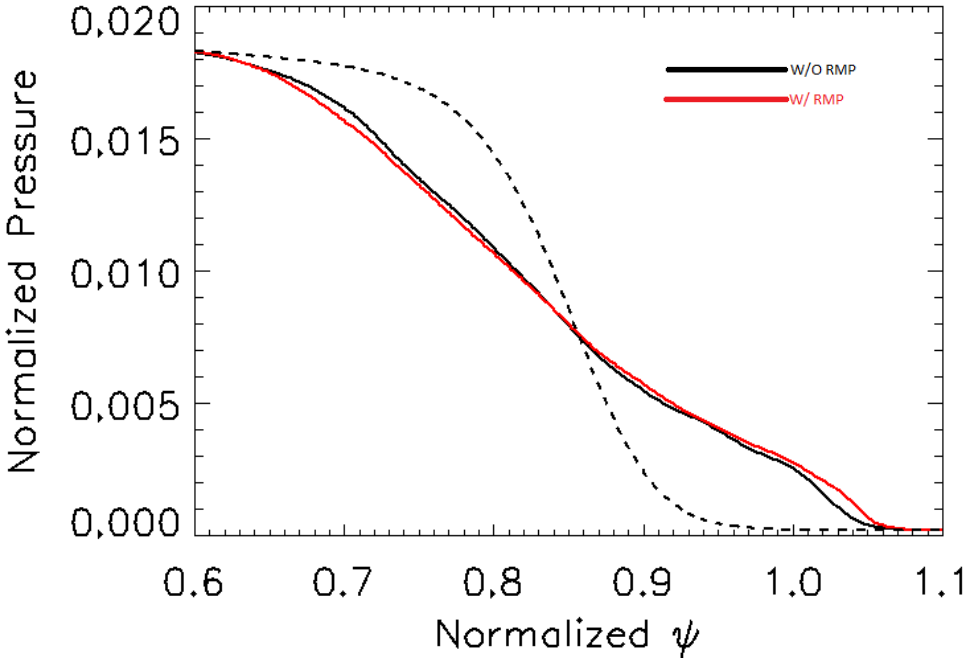


Nonlinear simulation, case 3

Definition of ELM size:

$$\Delta_{ELM}^{th} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\langle \int_{R_{in}}^{R_{out}} \oint dR d\theta (P_0 - \langle P \rangle_\zeta) \rangle_t}{\int_{R_{in}}^{R_{out}} \oint dR d\theta P_0},$$

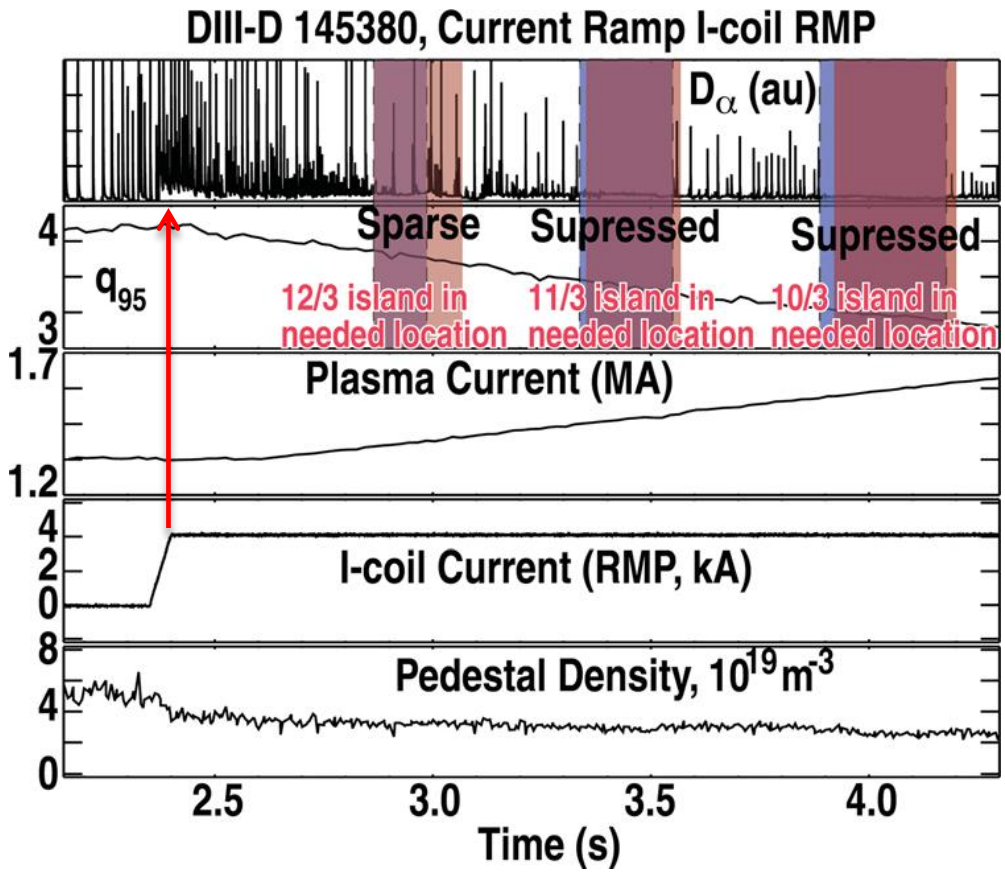




- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at t= 50 τ_A.

- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.

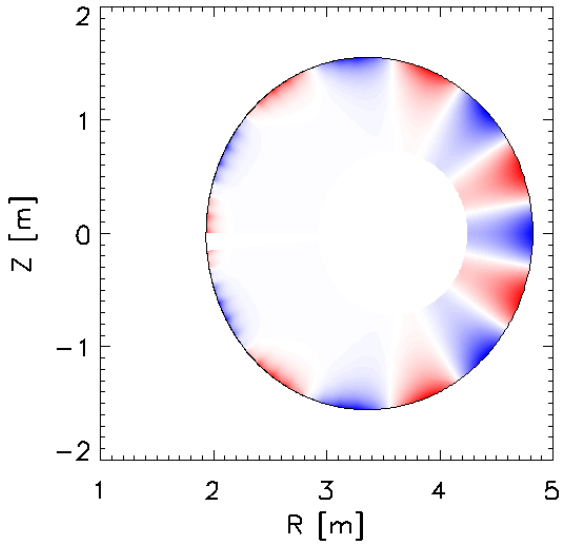
RMP experiments show that RMP field initially enhanced ELM activities

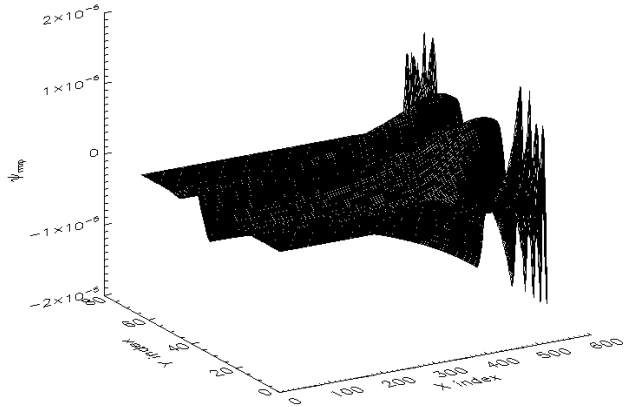


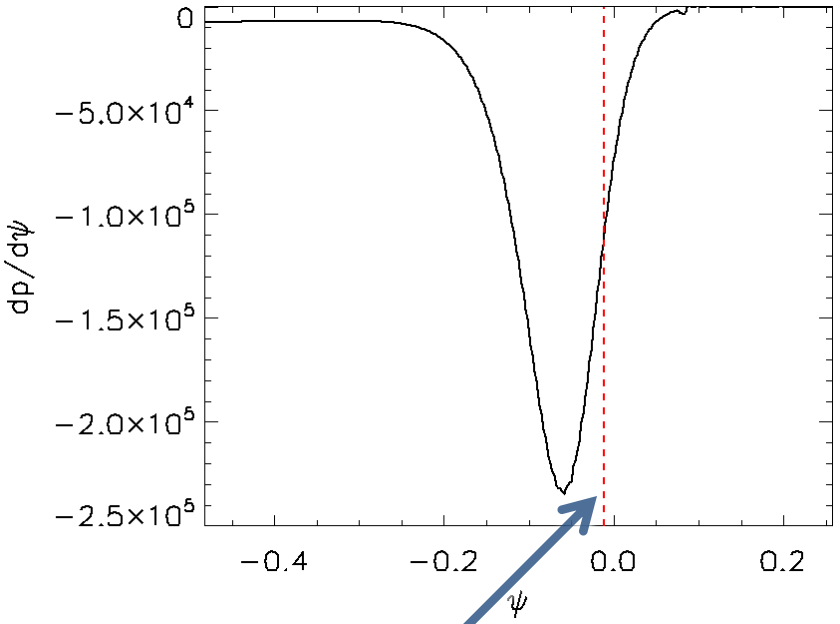
- Time traces showing the evolution of DIII-D discharge 145380 *[Snyder et al. PHYSICS OF PLASMAS 19, 056115, 2012].* When the I-coil current turn on, the D_α increased a little bit.

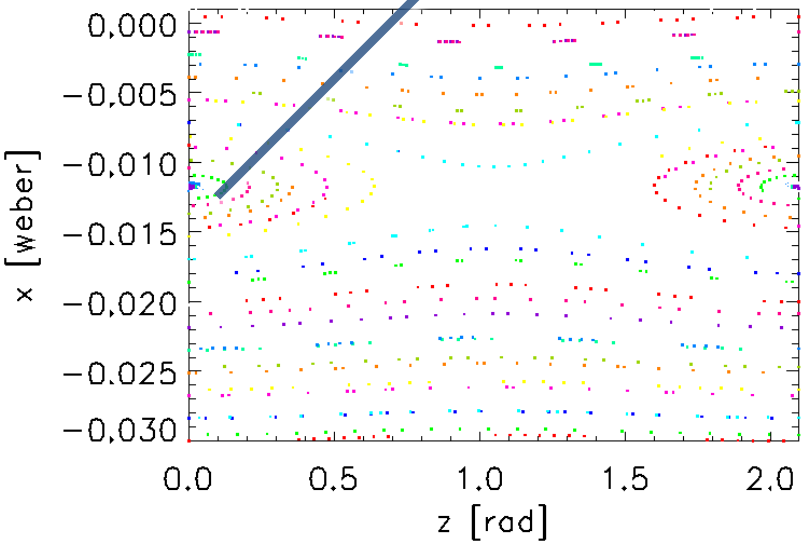
Nonlinear simulation, case 4

- Case 4:
- RMP: m=7, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens8

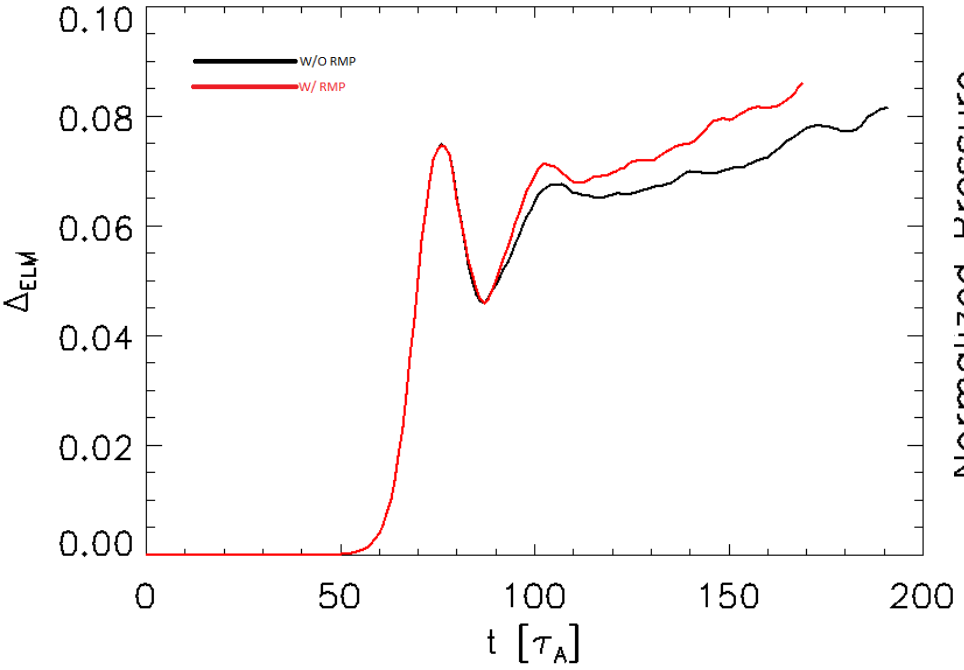


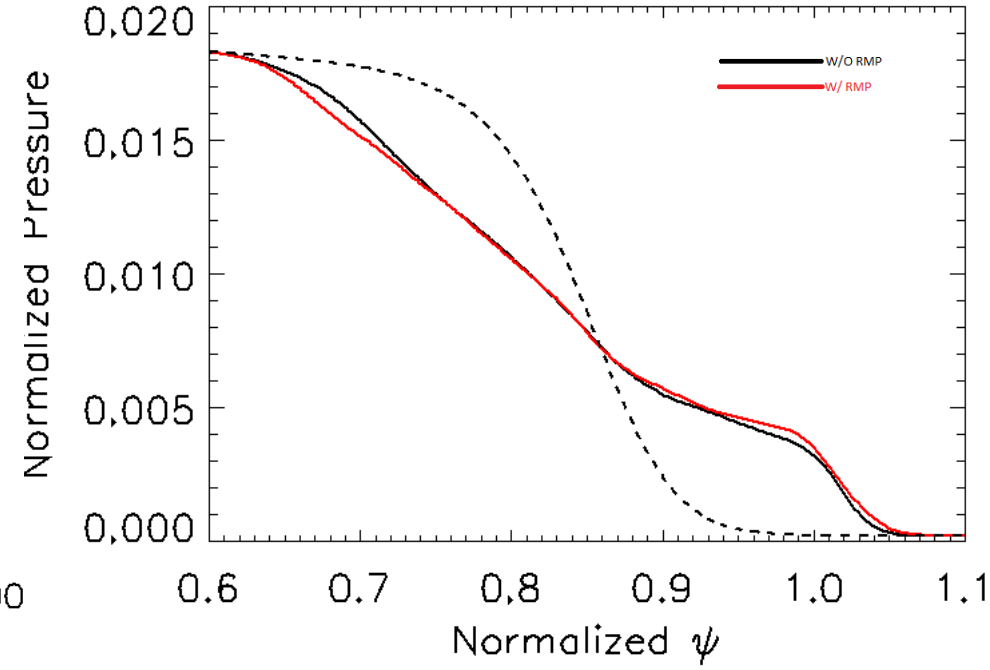






Nonlinear simulation, case 4



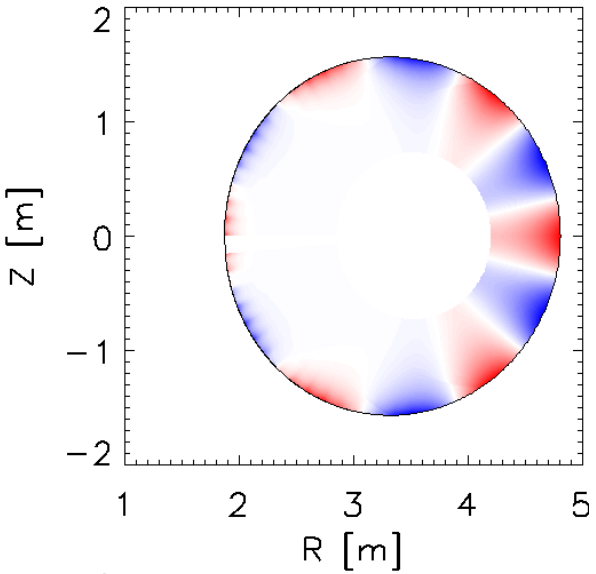


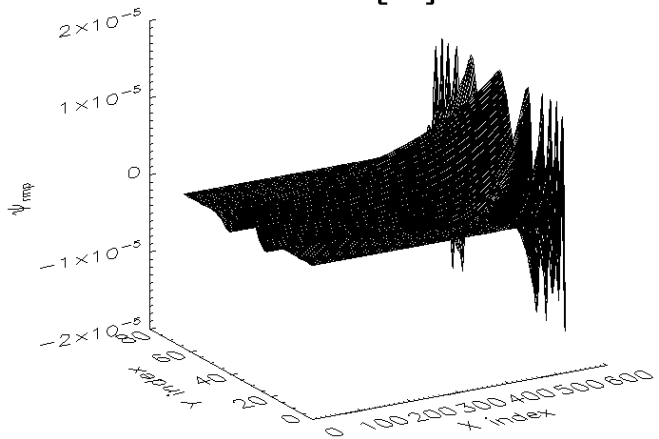
- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at t=50 τ_A.

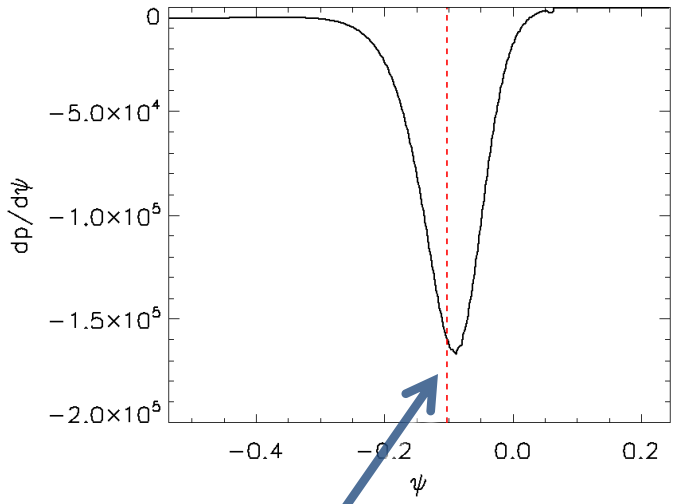
- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.

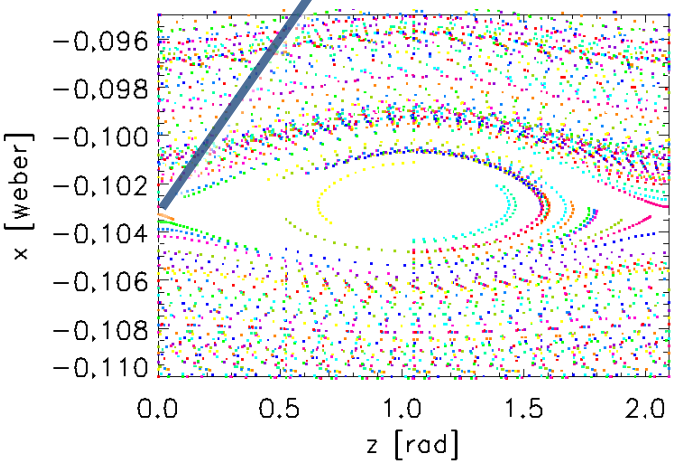
Nonlinear simulation, case 5

- Case 5:
- RMP: m=6, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6



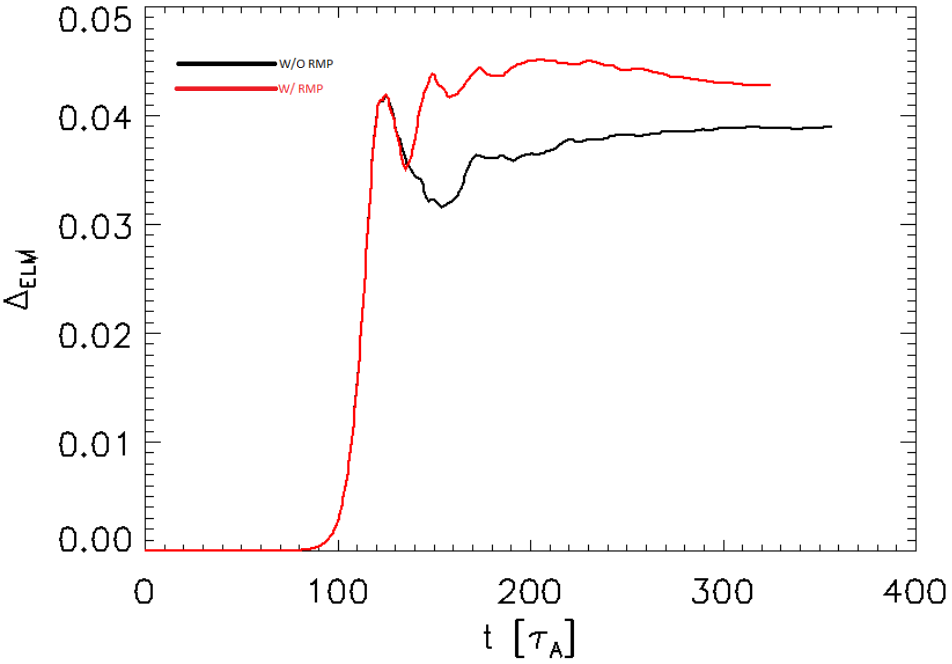


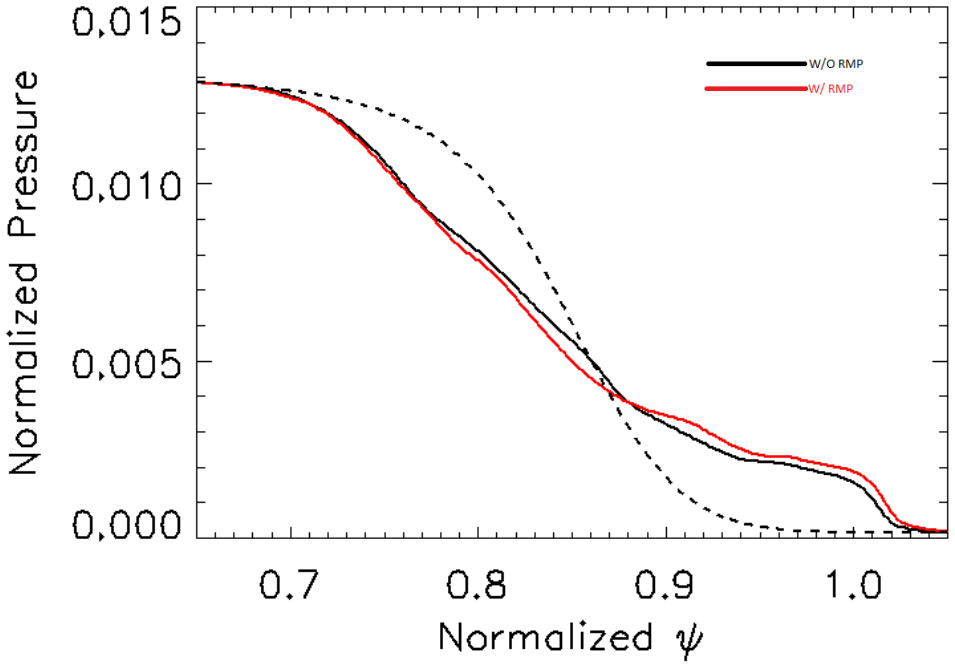




Nonlinear simulation, case 5

- Case 5:
- RMP: m=6, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6



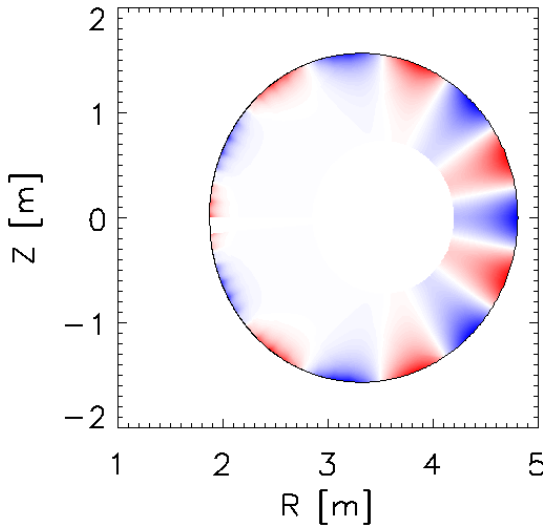


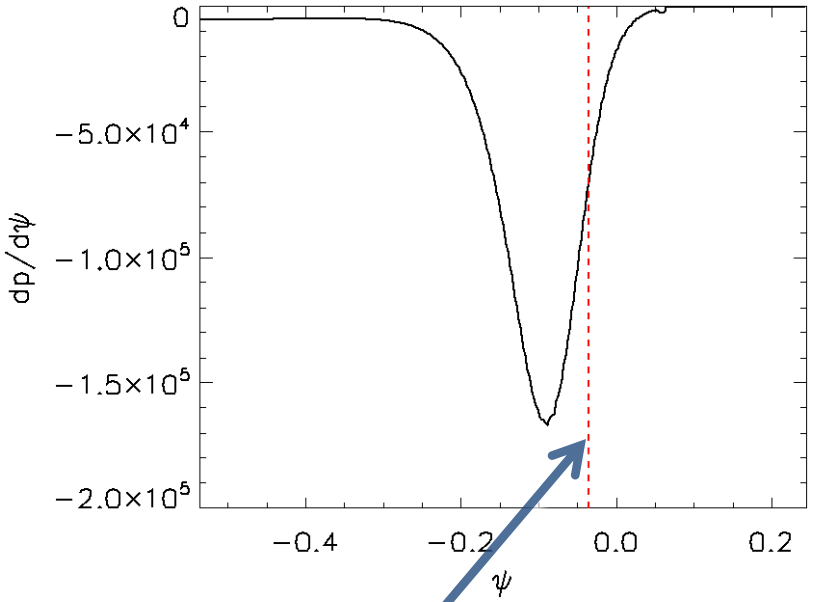
- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at t=80 τ_A.

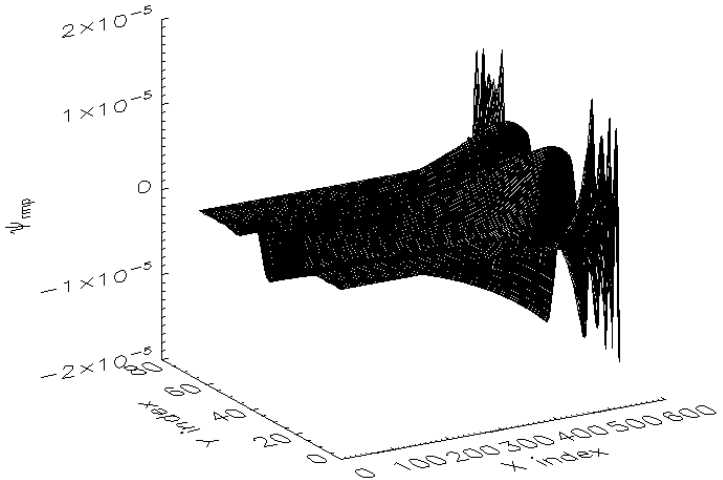
- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.

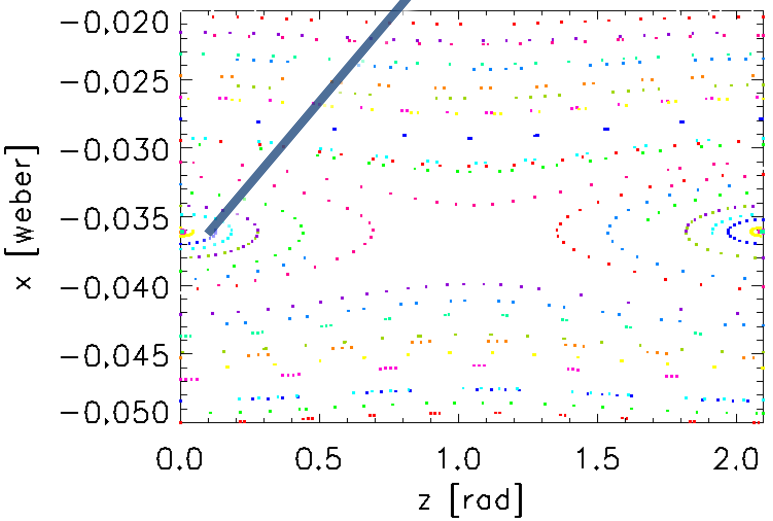
Nonlinear simulation, case 6

- Case 6:
- RMP: m=7, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6



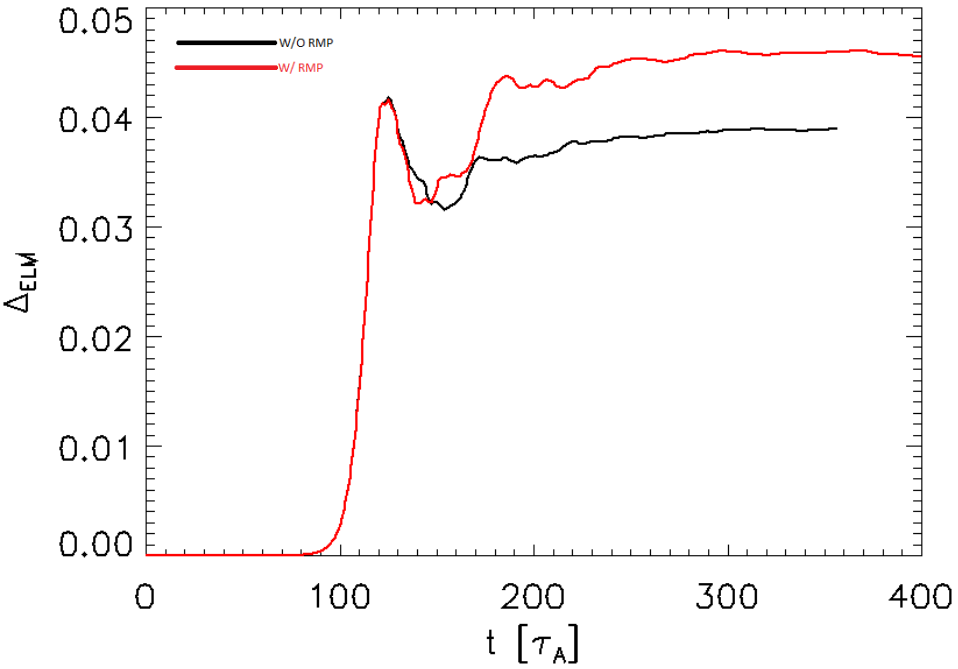


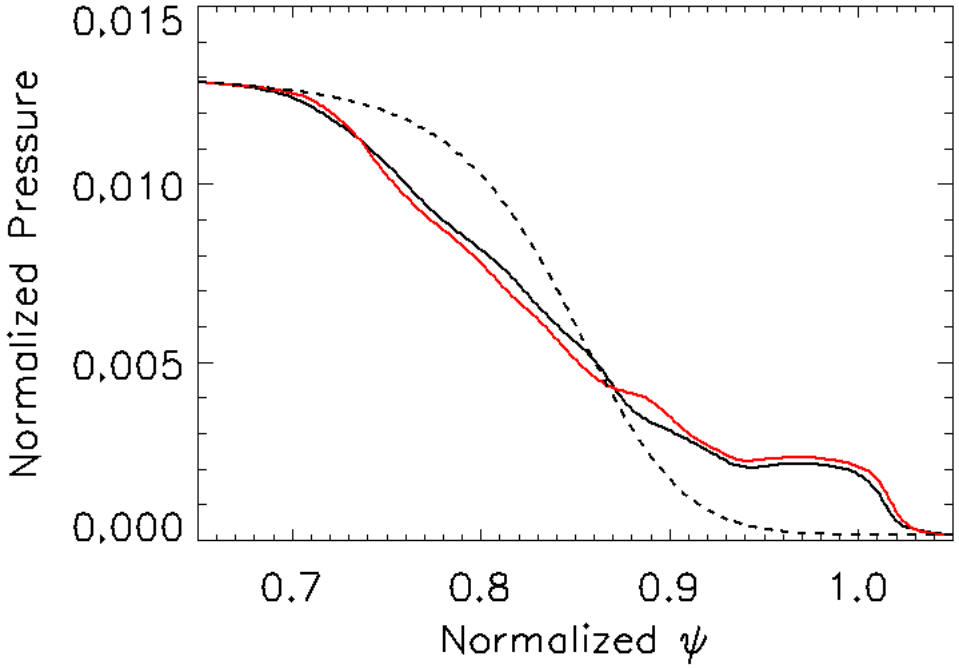




Nonlinear simulation, case 6

- Case 6:
- RMP: m=7, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6





- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at t=80 τ_A.

- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.

Conclusion

Case number	RMP field	Initial perturbation mode number	Results
Linear simulation			
Case 1	m=6, n=3	n=9	RMP could stabilizes the n=9 mode. RMP could change model spectrum. The dominated mode number changes from n=18 to n=21. The mode spectrum become wider.
Case 2	m=6, n=3	n=3	The dominated mode number changes from n=18 to n=21. The mode spectrum become wider.
Nonlinear simulation			
Case 3	m=6, n=3	n=15	RMP field could enhance ELM crash, thus the time averaged pressure profile become flatter than the case without RMP. For case 3, the magnetic filed island induced by RMP field is closed to the peak gradient position, so that RMP enhanced the ELM crash more significantly than the Case 4.
Case 4	m=7, n=3	n=15	The RMP filed has the same effect on ELM crash with Case 3, but the island is far from the peak gradient area compared with Case 3. The effect on ELM crash is also weaker.
Case 5	m=6, n=3	n=15	RMP field also enhance the ELM crash. The island position is same as the Case 3, but the 'dens6' equilibrium has the lower pedestal than the 'dens8' equilibrium and the P-B magnetic field perturbation is smaller, so that the RMP effect is more obvious than Case 3.
Case 6	m=7, n=3	n=15	Compared with the Case 5, the island is farther from the peak gradient area. The effect of RMP is weaker.